Real-Time Imaging of Cardiac Strain using Ultra-Fast HARP Sequence

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Introduction

Tagged MR imaging was introduced in 1988 and has been employed extensively for the non-invasive visualization of cardiac motion and detected the requirements for patients to breath-hold during the lengthy image acquisition times (8-20 heart beats per slice), and the subsequent laborious post-processing has limited its adoption as a quantitative clinical tool for diagnosis and monitoring.

The HARP technique [1] was proposed recently as a novel method for quantifying in-plane motion using MR tagging methodology. Tagged MR images comprise multiple spectral peaks (see Figure 1) in the Fourier domain. HARP exploits the fact that, when one of the off-center spectral peaks is isolated and inverse Fourier transformed, the phase of the resulting image is directly related to the motion of the underlying tissue. To date, this methodology has been demonstrated and validated as an extremely efficient means for extracting displacement and strain measurements from tagged MR datasets.

Here we describe the development of a pulse sequence and post-processing software specifically optimized for the real-time acquisition, reconstruction and display of HARP images capable of providing full visualization of the in-plane myocardial motion from just 2 cardiac cycles. This very short time acquisition significantly reduces (or eliminates) the burden of breath-holding for the patient.

Typically, 12-20 cardiac phases are acquired per R-R cycle with motion sensitivity switching (horizontal/vertical) on alternate heartbeats. The pulse sequence may be run continuously for cardiac motion sensitivity switching (horizontal/vertical) on alternate heartbeats. The pulse sequence may be run continuously for cardiac monitoring with the acquired HARP datasets being automatically reconstructed and displayed in real-time after each heart-beat.

Methods

All tests were conducted using a 1.5T Signa CV/i MRI system (General Electric Medical Systems, Waukesha, WI) equipped with 4G/cm imaging gradients. Gating was provided using an ECG monitor (Magnetic Resonance Equipment Corporation, Bayshore, NY) directly connected to the scanner.

The HARP pulse sequence comprises of a gated, multi-phase interleaved gradient-echo EPI pulse program. The sequence was modified to permit MR tagging immediately following R-wave detection using a 1-1 SPAMM scheme (two 90° rf pulses separated by a gradient pulse): the orientation and area of the tagging gradient pulse being determined from the tagging angle and tag separation scan parameters. The read dephaser and phase encoding gradients were modified to permit the acquisition of any one of the three k-space spectral peaks generated by the SPAMM preparation. A depiction of the k-space trajectory for the sequence is shown in Figure 2. To forestall the fading of the spectral peaks by T1 decay, to provide images with more constant intensity throughout the cardiac cycle, a train of increasing imaging flip angles can be used [2].

The receiver bandwidth of 62.5 KHz was determined to be an optimal compromise between acquisition time and SNR, for an echo train length of 8 with a TR of 11.3ms. Multiphase images (12-20/R-R) of a single slice (10mm thick) comprising 32x32 k-space samples were acquired in 4 interleaved shots (total acquisition time: 46ms/image), with an imaging FOV of 26cm. Tag directions were automatically switched (horizontal/vertical) on alternating heartbeats. A tag spacing of 8-9mm was used.

After each R-R interval, the acquired MR raw data for that heartbeat was automatically transferred to a Sun Ultra II external Workstation. The 4-coil, 32x32 data sets were interpolated to 128x128 during phase-sensitive reconstruction, and the resulting images were used to perform quantitative HARP analysis yielding displacement and strain maps and to generate synthetically tagged images. The synthetically tagged images were generated using data from the preceding 2 cardiac periods, providing data corresponding to horizontal and vertical tags respectively. New data from the nth R-R interval was used to replace that from the n-2th interval and an updated CINE loop was generated in real-time. Images were played out in real-time at the actual patient heart rate.

Results

Experiments were conducted on human volunteers to visualize normal heart motion. In all cases, the motion of the heart was clearly visualized in the synthetically tagged images and HARP strain maps. Figure 3 shows these images for a mid-systolic and an end-systolic time frame in a normal human. The darker colouration in the strain maps indicates more compression.

Discussion

An imaging pulse sequence optimized for the real-time acquisition of HARP images of the heart was developed and demonstrated. This sequence, in combination with HARP real-time analysis tools, provides a clinical cardiac monitoring tool with the potential application for providing real-time quantification of regional dysfunctions during clinical dobutamine stress tests.

References


Fig.1. Fourier Transform of a Tagged Image

Fig.2. Single Peak Acquisition

Fig.3. Synthetic Tags, Eulerian Strain at A. mid-systole and B. end-systole